## VII. "On the Constituent of the Atmosphere which absorbs Radiant Heat." By S. A. Hill, B.Sc., Meteorological Reporter for the North-Western Provinces and Oudh, India." Communicated by Lieut.-General R. Strachey, R.E., F.R.S. Received December 14, 1881.

Notwithstanding the ingenuity with which Dr. Tyndall has made use of the most recent physical appliances to support and confirm the results of his classical researches concerning the behaviour of gases and vapours with regard to radiant heat, his conclusions, in so far as they relate to the comparative diathermancy of dry air and water vapour, have not yet met with general acceptance among meteorologists. There is even, on the part of some, an evident reluctance to accept the decision of laboratory experiments on the question of atmospheric absorption as final, however ingenious, varied, and consistent with one another the experiments may be.

I have, therefore, attempted to approach the question from another side, and to determine, if possible, what constituent of the atmosphere has the greatest absorptive power, by means of the actinometric observations so carefully made at Mussooree and Dehra by Messrs. J. B. N. Hennessey, F.R.S., and W. H. Cole, M.A., in conjunction with the records of meteorological observations made at the same or neighbouring places in the same months of the year. The actinometric observations were made between the 27th October and 4th November, 1869, and between the 31st October and 19th November, 1879. Abstracts of the results have been published by Mr. Hennessey in the "Proceedings," vol. xix, p. 229, and vol. xxxi, p. 154. In both years the observations were made with two actinometers of the Rev. G. C. Hodgkinson's form, marked A and B, each of which appears to have remained absolutely unaltered during the ten years. The results taken from Mr. Hennessey's tables are those expressed in units equal to a tenth of a millimetre of the scale of the instrument A, *glass off*.

The observations which serve to throw most light on the question under discussion are those of the long diurnal series, from 8 A.M. to 4 P.M., made on the 4th November, 1869, and the 12th and 14th November, 1879. In Tables I, II, III, the observed values of the radiation received in three minutes at each hour* are compared with certain symmetrical values computed in the following way.

It has been assumed that Jamin and Masson's law of absorption holds good for each day at both stations; that is to say, that the logarithm of the heat received varies inversely as the thickness of the atmosphere traversed, or, in other words, that the quantity of heat

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* On the 4th November, 1869, the mean time of each set of observations was several minutes after the exact hour. The values given in Table I have been interpolated from Mr. Hennessey's figures by means of parabolic formulæ extending over three hours at a time.

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absorbed by each unit thickness of the absorbent substance (supposed homogeneous) is proportional to the total heat which falls upon it. This rule was long ago found by Pouillet to be approximately true of atmospheric absorption. The thickness of atmosphere to be traversed by the solar rays at various angles of incidence has been taken to be simply proportional to the secant of the sun's zenith distance. If the vertical thickness of the absorbent atmosphere be taken at $\frac{1}{400}$th of the earth's radius, the error of the preceding assumption is almost insensible for the inclinations in the tables; and below an elevation equal to $\frac{1}{400}$th of the radius lie 68 per cent. of the dry air, and 99½ per cent. of the water vapour of our atmosphere. If, then, R stands for the total radiation that would fall upon the actinometer at the limit of the atmosphere, and $r$ for the observed radiation at the place of observation, when the sun's zenith distance is $z$, we may put $\log r = \log R - K \sec z$, where K is a coefficient the antilogarithm of which represents the fraction of the total radiation that would be absorbed by a vertical column of the air above the place at the time of the observation. Assuming the K to be constant for each day at each station, I have computed the values of log R independently from the sets of observations made at the two stations; and then, taking the most probable value of R for each day to be that derived from the mean of the two log R's, in which the logarithm deduced from the observations at the upper station* is given double weight, I have recomputed the coefficients marked $K_M$ and $K_D$ respectively, and finally worked out the symmetrical values of $r$ for the hours before and after apparent noon.

Table I.—4th November, 1869.

| Hour. Appt. time. | Mussooree. | | | | Dehra. | | | |
|---|---|---|---|---|---|---|---|---|
| | Sec $z$. | $r$ obs. | $r$ comp. | Diff. | Sec $z$. | $r$ obs. | $r$ comp. | Diff. |
| 8 A.M. .... | 3·57 | 842 | 817 | −25 | 3·54 | 715 | 645 | −70 |
| 9 ,, .... | 2·21 | 934 | 929 | − 5 | 2·20 | 807 | 801 | − 6 |
| 10 ,, .... | 1·71 | 990 | 973 | −17 | 1·70 | 870 | 868 | − 2 |
| 11 ,, .... | 1·50 | 1000 | 993 | − 7 | 1·49 | 905 | 898 | − 7 |
| Noon .... | 1·43 | 988 | 999 | +11 | 1·43 | 914 | 907 | − 7 |
| 1 P.M. .... | 1·50 | 984 | 993 | + 9 | 1·49 | 900 | 898 | − 2 |
| 2 ,, .... | 1·71 | 967 | 973 | + 6 | 1·70 | 852 | 868 | +16 |
| 3 ,, .... | 2·21 | 920 | 929 | + 9 | 2·20 | 786 | 801 | +15 |
| 4 ,, .... | 3·57 | 799 | 817 | +18 | 3·54 | 584 | 645 | +61 |

Mean R = 1143 $\log R = 3·05804$
$K_M$ = ·04078 for decimal logs
= ·09390 ,, natural ,,
$K_D$ = ·07027 ,, decimal ,,
= ·16157 ,, natural ,,
$\frac{K_M}{K_D} = ·5803$

* Dehra is 2,229 feet above the sea, and Mussooree 6,937 feet.

### Table II.—12th November, 1879.

| Hour. Appt. time. | Mussooree. | | | | Dehra. | | | |
|---|---|---|---|---|---|---|---|---|
| | Sec *z*. | *r* obs. | *r* comp. | Diff. | Sec *z*. | *r* obs. | *r* comp. | Diff. |
| 8 A.M. .... | 3·90 | 744 | 736 | − 8 | 3·89 | 622 | 610 | −12 |
| 9 „ .... | 2·36 | 873 | 852 | −21 | 2·34 | 764 | 762 | − 2 |
| 10 „ .... | 1·80 | 907 | 898 | − 9 | 1·79 | 817 | 824 | + 7 |
| 11 „ .... | 1·56 | 925 | 918 | − 7 | 1·55 | 851 | 853 | + 2 |
| Noon .... | 1·50 | 934 | 924 | −10 | 1·49 | 850 | 860 | +10 |
| 1 P.M. .... | 1·56 | 915 | 918 | + 3 | 1·55 | 840 | 853 | +13 |
| 2 „ .... | 1·80 | 876 | 898 | +22 | 1·79 | 847 | 824 | −23 |
| 3 „ .... | 2·36 | 832 | 852 | +20 | 2·34 | 771 | 762 | − 9 |
| 4 „ .... | 3·90 | 727 | 736 | + 9 | 3·89 | 596 | 610 | +14 |

Mean R = 1064 log R = 3·0271
$K_M$ = ·04106 for decimal logs
= ·09454 „ natural „
$K_D$ = ·06209 „ decimal „
= ·14297 „ natural „
$\frac{K_M}{K_D} = \cdot 661$

### Table III.—14th November, 1879.

| Hour. Appt. time. | Mussooree. | | | | Dehra. | | | |
|---|---|---|---|---|---|---|---|---|
| | Sec *z*. | *r* obs. | *r* comp. | Diff. | Sec *z*. | *r* obs. | *r* comp. | Diff. |
| 8 A.M. .... | 3·99 | 785 | 762 | −23 | 3·97 | 639 | 617 | −22 |
| 9 „ .... | 2·38 | 888 | 892 | + 4 | 2·37 | 766 | 786 | +20 |
| 10 „ .... | 1·82 | 941 | 941 | 0 | 1·81 | 848 | 855 | + 7 |
| 11 „ .... | 1·58 | 966 | 963 | − 3 | 1·58 | 883 | 884 | + 1 |
| Noon .... | 1·51 | 978 | 970 | − 8 | 1·51 | 892 | 894 | + 2 |
| 1 P.M. .... | 1·58 | 947 | 963 | +16 | 1·58 | 899 | 884 | −15 |
| 2 „ .... | 1·82 | 938 | 941 | + 3 | 1·81 | 849 | 855 | + 6 |
| 3 „ .... | 2·38 | 873 | 892 | +19 | 2·37 | 780 | 786 | + 6 |
| 4 „ .... | 3·99 | 762 | 762 | 0 | 3·97 | 620 | 617 | − 3 |

Mean R = 1123 nearly log R = 3·050483
$K_M$ = ·04231 for decimal logs
= ·09742 „ natural „
$K_D$ = ·06546 „ decimal „
= ·15063 „ natural „
$\frac{K_M}{K_D} = \cdot 644$

These tables suggest two independent methods of inquiring which among the atmospheric gases has the greatest power of arresting radiant heat. We can inquire which constituent of the atmosphere is subject to a diurnal variation most resembling that of the absorption coefficient, and also which constituent is distributed vertically in a manner most closely approaching to that of the absorptive substance.

If the coefficient K were truly constant for each day, as has been assumed, the positive and negative differences between the observed and computed values of $r$ should be irregularly distributed; but we find that, almost without exception, the computed values are too low in the forenoon and too high in the afternoon at Mussooree, while at Dehra there is no such regular order in the differences. The excess of the morning over the afternoon radiation at Mussooree and their approximate equality at Dehra are very clearly seen in the averages of the three sets of observations, which are the following:—

| Hour ....... | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|
| Mussooree .. | 790 | 898 | 946 | 964 | 967 | 949 | 927 | 875 | 763 |
| Dehra ...... | 659 | 779 | 845 | 880 | 885 | 880 | 849 | 779 | 600 |

The departure from complete symmetry at Dehra is due chiefly to one observation at 4 P.M. on the 4th November, 1869, when probably there was a slight haze partially obscuring the sun.

The absorption of heat by the atmosphere on a clear, calm day cannot be, in any appreciable degree, a mere apparent effect due to the scattering of the rays brought about by disturbances set up in the atmosphere through heating from below; for any variations in the amount of such scattering must be even more apparent at the lower station that at the upper one, because, to get to the lower station, the rays must pass through more of the disturbed atmosphere. Moreover, such disturbances, and the apparent absorption caused by them, would probably be at least as great during the hours of rising temperature (up to about 1 P.M.) as when the temperature is falling. The increased absorption of the afternoons at Mussooree must therefore be due to the fact that more of the absorbent substance—whatever it be—lies above the level of the station in the afternoons than in the mornings, while above the lower station the total quantity of this substance is practically constant throughout the day; that is to say, the absorbent substance is carried upwards during the day and probably sinks downwards again at night.

Such an upward movement of the total atmosphere occurs under the influence of diurnal heating, but what proportion of the air that is lifted above Mussooree by expansion from below remains there cannot be exactly determined. The barometer falls from 10 A.M. to

4 P.M. at all elevations where observations have been made in the Himalaya, as it does on the plains. In any case, the fraction of the total atmosphere which accumulates above Mussooree during the day hours must be a very small one, and its influence in increasing the absorptive power of the upper atmosphere may be safely neglected.

With water vapour the case is different. This diminishes so rapidly as we ascend* that, if it be the chief absorbent substance, a small variation in the quantity of it lying above the higher station will considerably affect the absorbing power there observed. In the following table the value of $K_M$ for each hour of observation, computed from the mean of the three series, is compared with the mean hourly values of the barometric pressure and vapour tension for November at Simla, a neighbouring station of nearly the same altitude, and with the vapour tension and cloud proportion observed at Roorkee, a station 40 miles S.S W. from Mussooree and 887 feet above the sea. General Boileau's observations at Simla in 1843–5, from which the figures for that station have been taken, were made inside a house, and do not strictly represent the variations in the humidity of the external air. The normal variation of humidity in the upper air may, however, be inferred with some approximation to the truth from the variations of cloud; for though the days of observation were without cloud, like most days in November in North India, there is no reason to suppose that the diurnal movements of the vapour were different in direction on those days from what they are when the humidity is so high that clouds are formed.

Table IV.

| Hour. | Absorption coefficient. Mussooree. | Barometric pressure. Simla. | Vapour tension. Simla. | Cloud proportion. Roorkee. | Vapour tension. Roorkee. |
|---|---|---|---|---|---|
| 8 A.M.... | ·03862 | 23·323″ | ·166″ | 0·99 | ·346″ |
| 9 " .... | ·03966 | 23·349 | ·172 | 0·90 | ·367 |
| 10 " .... | ·03908 | 23·360 | ·179 | 0·80 | ·373 |
| 11 " .... | ·03969 | 23·353 | ·186 | 0·81 | ·372 |
| Noon .... | ·04051 | 23·333 | ·194 | 0·90 | ·362 |
| 1 P.M.... | ·04409 | 23·307 | ·198 | 1·10 | ·344 |
| 2 " .... | ·04405 | 23·283 | ·200 | 1·25 | ·332 |
| 3 " .... | ·04416 | 23·267 | ·202 | 1·26 | ·332 |
| 4 " .... | ·04264 | 23·259 | ·204 | 1·23 | ·354 |

It will be seen from Table IV, and from the diagram below, that the variation of the absorption coefficient is similar in its chief feature—the increase from morning to afternoon—to that of the vapour pressure observed at Simla, but totally different from the variation of the barometric pressure; while the absorption curve agrees closely with that of the humidity of the upper atmosphere as indicated by cloud, even in minor points like the decrease at 10 A.M.

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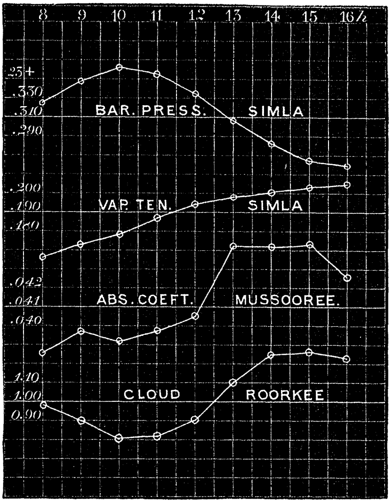
* See Strachey, "Proc. Roy. Soc." (vol. 11, p. 182).



Also, since the hourly observations at Roorkee show that the pressure of vapour there is less in the afternoon than in the morning, it is probable that the variations, both above and below, are caused by an upward movement of the vapour during the day. Such a movement would not affect the absorption of heat by the whole depth of the atmosphere, if water vapour be the chief absorbent substance, and we find that at Dehra the absorption in the afternoon is little, if at all, greater than in the morning. The evidence of the diurnal variation, therefore, points strongly to the conclusion that water vapour is the chief absorbent.

The question may be answered more directly by the second method, the determination of the law of vertical distribution of the absorbing matter. Since both stations lie above the dust-haze so common over India in the cold weather, and since the days of observation were free from cloud, we may assume that the absorbent substance we have to deal with is a gas distributed according to the barometric formula; and therefore the observations at two places suffice to determine the law approximately. We have, then, for each day, $\log K_M = \log K_D - \frac{\Delta h}{C}$, where $\Delta h$ is 4,708 feet and C is a constant for the day. Computing C in this way for each day, and also $C_1$ and $C_2$ for the dry air and water vapour respectively, taking $\frac{1}{C_1}=\frac{\log B_D-\log B_M}{\Delta h}$; $\frac{1}{C_2}=\frac{\log f_D-\log f_M}{\Delta h}$ where $f$ is the vapour tension, and B the height of the barometer corrected for vapour tension, we get the following values :—

| Date. | C | $C_1$ | $C_2$ |
|---|---|---|---|
| 4th November, 1869 ........ | 19,922 | 64,409 | 17,210* |
| 12th ,, 1879 ........ | 26,213 | 66,370 | 26,814 |
| 14th ,, ,, ........ | 24,840 | 66,066 | 25,499 |
| Mean .................... | 23,658 | 65,615 | 23,174 |

In computing $C_2$ the vapour tensions observed at the Meteorological Observatory of Roorkee have been combined with those of Dehra, because the latter seem to be somewhat too great at all times of the year in comparison with those for other places in the Himalaya at nearly the same altitude,† while Roorkee is generally a little too dry. In any case, with such a variable element as water vapour, it is best to deduce the law of distribution from as many observations as possible.

The difference between the values of C and $C_2$ is so small, considering the nature of the observations, while that between C and $C_1$ is so very great, that there can be very little error in agreeing with Dr. Tyndall that the absorptive power of dry air is sensibly nothing, and that the total absorptive power of the atmosphere is due to the water vapour it contains.

The true absorption coefficient at sea-level, on the supposition that the absorbent substance increases in density according to the same law as between Mussooree and Dehra, appears to have been a good deal less on the two days of observation in 1879 than the mean value found by Pouillet in 1838, while its value on the 4th November, 1869, differed but little from Pouillet's mean result. Pouillet found the absorption of a vertical column of transparent atmosphere at Paris to vary between ·18 and ·27 of the total incident radiation, the mean being about ·24. From Mr. Hennessey's observations the coefficient for Naperian logarithms at sea-level appears to have been

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* Computed from the observations made at the Meteorological Observatories of Dehra and Roorkee, and at Chakrata, 30 miles north of Mussooree and 7,160 feet above the sea. No observations of humidity were made at Mussooree on this day.

† This has been pointed out by the writer in a paper on the meteorology of the North West Himalaya, published in the "Indian Meteorological Memoirs," vol. i.

·209 on the 4th November, 1869, and ·174 and ·185 respectively on the 12th and 14th November, 1879.

If the differences in these values of the total absorption be caused entirely by variations in the quantity of aqueous vapour in the air, the fraction of the total incident heat which is arrested before reaching the ground will be a direct function of the vapour tension at the place of observation, and an inverse function of the rate of diminution of the vapour tension with height. We may suppose it to be simply proportional to the total quantity of water vapour over the place of observation. This has been shown by Dr. J. Hann* to be equal to a depth of water, $f\times\frac{\cdot 0010582}{1+\alpha t}\times\cdot 4343\ C$, where $f$ is the vapour pressure expressed in units of height of mercury, and C is the constant of the vapour formula in metres. Neglecting the temperature coefficient, which should probably enter into C also, and reducing to English measure, the quantity of rain that would be formed by the complete condensation of the vapour over any place is given by the formula, $Q=f\times\cdot 00014\ C$ inches, where $f$ is expressed in inches of mercury, Q in inches of water, and C in feet. At Mussooree, on the days of observation in 1879, the several quantities had the following values :—

| Date. | K | $f$ | $C_2$ | Q |
|---|---|---|---|---|
| 12th November ...... | ·04106 | ·221″ | 26,814 ft. | ·829″ |
| 14th " ...... | ·04231 | ·183 | 25,499 | ·653 |

If now $K=\alpha Q$, the value of $\alpha$ on the 12th November is found to be ·0495, and on the 14th, ·0648. The fraction of the total radiation absorbed from day to day therefore does not bear a constant relation to the quantity of aqueous vapour in the air; and, consequently, it seems probable that the *quality* of the sun's heat is subject to considerable variations from day to day. If this be so, it will be impossible to arrive at comparable actinometric results from a few observations about apparent noon each day, unless the observing station be sufficiently elevated to lie above the greater part of vapour atmosphere.

Unfortunately no hygrometric observations were taken at Mussooree in November, 1869, so that it is impossible to determine precisely, from the actinometric observations made there by Mr. Hennessey, whether the radiation emitted from the sun was more or less susceptible of absorption in 1869 than in 1879. At Dehra, however, the psychrometer was observed every day at 9.30 A.M. and 3.30 P.M., and from these observations, in conjunction with the figures already given, we can find an approximate value of $a$ for the 4th November, 1869, as well as for the two days in 1879. In the following table the quantities from which $a$ is computed and its value for each day are shown:—

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* "Zeitschrift für Meteorologie," Band IX, page 199.

| Date. | K | $f$ | $C_2$ | Q | $\alpha$ |
|---|---|---|---|---|---|
| 4th November, 1869.. | ·07027 | ·344″ | 17,210 ft. | ·829″ | ·0848 |
| 12th „ 1879.. | ·06209 | ·375 | 26,814 | 1·407 | ·0441 |
| 14th „ „ .. | ·06546 | ·302 | 25,499 | 1·078 | ·0607 |

The vapour tension observed at Dehra is a strictly local phenomenon, as has been above pointed out, but still the values of $a$ for the two days in 1879 accord so well with those deduced from the observations at Mussooree, that there can be little doubt that water vapour had a greater absorbent effect on the radiation of the 4th November, 1869, than on that emitted from the sun on the other days.

From the observations made simultaneously at Mussooree and Dehra, for several days near apparent noon, we may perhaps determine approximately whether the mean emissive power of the sun was greater at the beginning of November, 1869, or in November, 1879. There are only three quantities to determine for each year, the total radiation at the limit of the atmosphere, the absorption coefficient for Mussooree and the same for Dehra, and we have three relations between these quantities:—

$$(1)\ \text{Log R} = \log r_M + K_M \sec z_M,$$

$$(2)\ \text{Log R} = \log r_D + K_D \sec z_D,$$

$$(3)\ \text{Log K}_M = \log K_D - \frac{4{,}708 \text{ feet}}{C}.$$

In (3) we may take C to be the constant of the formula for water vapour, which, for 1869, may be computed from the observations at Roorkee, Dehra, and Chakrâta. From Mr. Hennessey's tables and the Meteorological Observatory records, I find the following mean values for the required data:—

| Year. | $r_M$ | $r_D$ | Sec $z_M$ | Sec $z_D$ | C. |
|---|---|---|---|---|---|
| 1869 | 980 | 902 | 1·401 | 1·398 | 19,077 |
| 1879 | 954 | 887 | 1·475 | 1·471 | 25,030 |

These data yield the following results :—

| Year. | R. | $K_M$ | $K_D$ | True K at sea-level. |
|---|---|---|---|---|
| 1869 | 1095 | ·03454 | ·06094 | ·1836 |
| 1879 | 1093 | ·03995 | ·06160 | ·1741 |

As far as we can judge from seven days' observations in 1869 and sixteen days in 1879, it would seem that the mean radiation of the sun, and the mean absorption of the atmosphere lying above Dehra were practically the same in the two years; while the absorption at Mussooree was slightly greater, and that at sea-level somewhat less in 1879 than in 1869.

On the mean of all the days the quantity of water vapour in the air above Dehra was equal to ·846 inch of rain in 1869, and 1·174 inch in 1879; and the corresponding values of $\alpha$, the coefficient of absorption for common logarithms, when the water vapour is equal to an inch of rain, were ·072 and ·0525 respectively. The vapour tensions at Dehra are of too local a character to admit of any safe inference from these figures; but, as far as the evidence goes, it points to the conclusion that the radiation emitted by the sun during the days of observation in 1869 was more readily absorbed by water vapour than that emitted in 1879.

It is to be hoped that the observations which are to be commenced next year at Leh—a station 11,500 feet above the sea—that is, lying above four-fifths of the absorbent atmosphere—will enable us to solve the all-important problem whether the sun's heat varies to any appreciable extent or not; but simultaneous observations at a lower station, such as Mussooree, will be required to settle without doubt the further question, whether there is any sensible variation in the quality of the solar rays, as tested by actinometric methods, that can be compared with the changes in the absorption lines which are observed in the spectra of spots.

Since writing the above, I have seen a report of a lecture* by M. Violle, Professor at the Faculté des Sciences, Grenoble, in which the lecturer described some simultaneous observations made by himself and another at the summit of Mont Blanc and Grenoble, and at the Grands Mulets and Glacier des Bossons, on the 16th and 17th of August, 1875. M. Violle's values for the heat received in a minute by a square centimetre of surface exposed perpendicularly to the sun's rays are given in calories in the following table :—

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* "Revue Scientifique," April 6, 1878.

| Date. | Place. | Altitude. (feet). | Heat received per minute. |
|---|---|---|---|
| August, 1875 ...... | Limit of atmosphere .... | ? | 2·54 |
| „ 16th ...... | Mont Blanc ............ | 15,780 | 2·39 |
| „ 17th ...... | Grands Mulets ........ | 10,010 | 2·26 |
| „ 17th ...... | Glacier des Bossons...... | 3,940 | 2·02 |
| „ 16th ...... | Grenoble .............. | 700 | 1·81 |

From these results M. Violle concluded that the absorptive effect due to water vapour was about five times as great as that due to dry air; but when the constant C, of the logarithmic formula for the vertical distribution of the absorbent substance is computed, it is found to be 22,137 feet on the 16th August and 22,580 on the 17th. These numbers agree so closely with the mean of those found above, and with the constant of the average vapour formula found by Dr. Hann,† viz., 6,517 metres or 21,382 feet, that it is evident that in the Alps, as in the Himalayas, practically the whole absorptive power of the atmosphere is exercised by the water vapour it contains.

The Society adjourned over the Christmas Recess to Thursday, January 12th, 1882.

## *Presents, December* 8, 1881.

Transactions.

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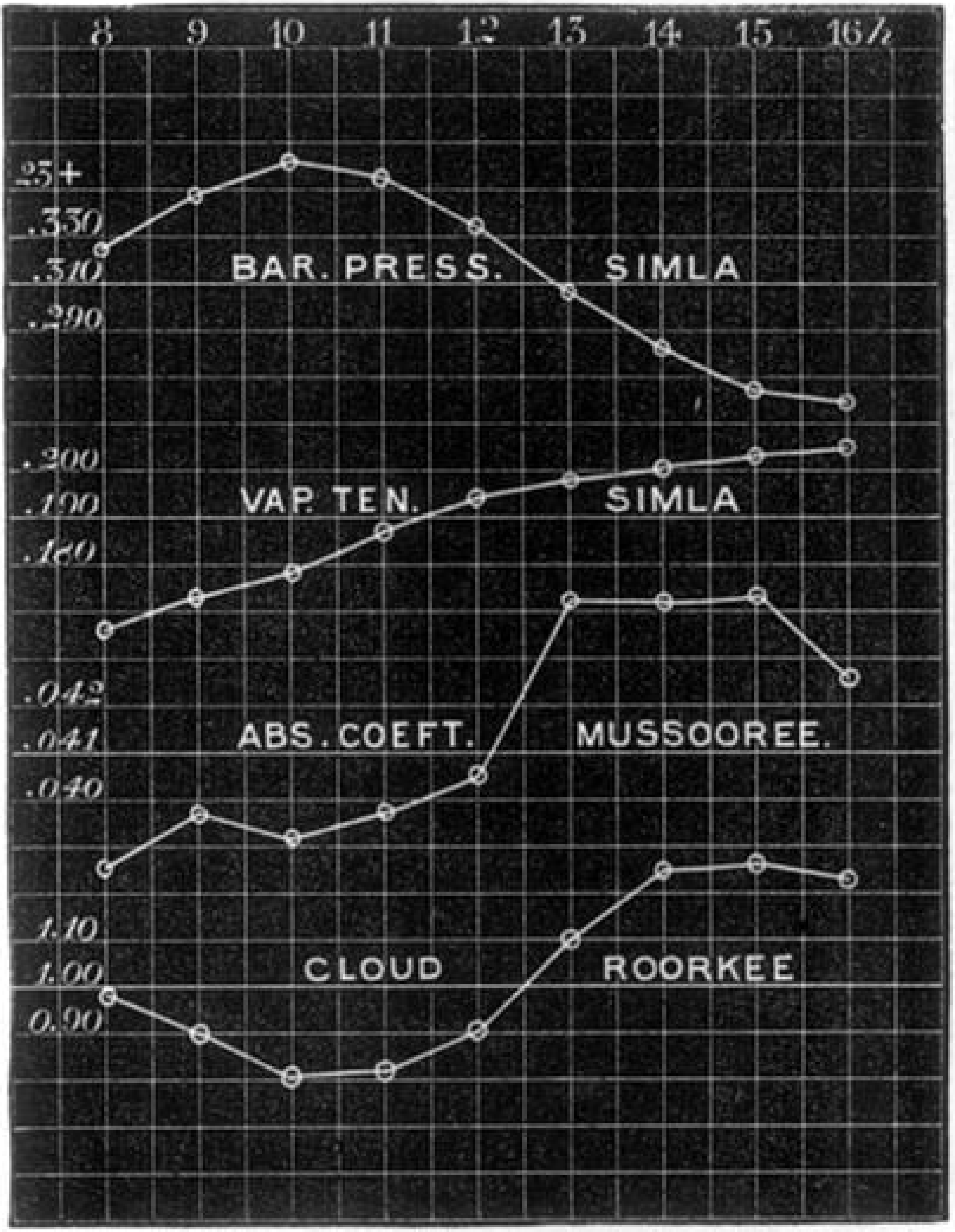
* *Loc. cit.*



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